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# Ionization and Attraction of Neutral Molecules to a Charged Spacecraft

Prepared by  
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Interim Report

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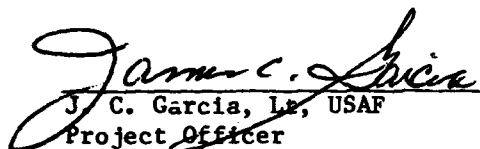
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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Neutral molecules given off by spacecraft outgassing or thrusters may become ionized by solar uv radiation or ambient energetic electrons. These ions may be reattracted to the spacecraft and hence constitute a source of contamination for sensitive spacecraft surfaces. In this report, the magnitude of this effect is calculated. Comparable fluxes of ions are found to be produced by uv radiation and by electrons. It is predicted that 0.02 percent of the heavy neutral spacecraft effluents will be ionized within the spacecraft			

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plasma sheath, and all of these will be returned to a negatively charged spacecraft. Using the best available outgas fluxes, it is also predicted that the reattraction of outgas products will be a significant contaminating effect during the initial several months of the spacecraft's orbital lifetime, second only to direct contaminant impingement. Together these effects deposit 100 Å of contaminants in the first 6 months. The ionization/reattraction mechanism cannot be ruled out on the basis of present data. The implications of assuming that this contamination mechanism is the dominant one during the early spacecraft lifetime are examined. In addition, a list of parameters that need to be measured more accurately is presented, and ways to combat contamination from this source are outlined.

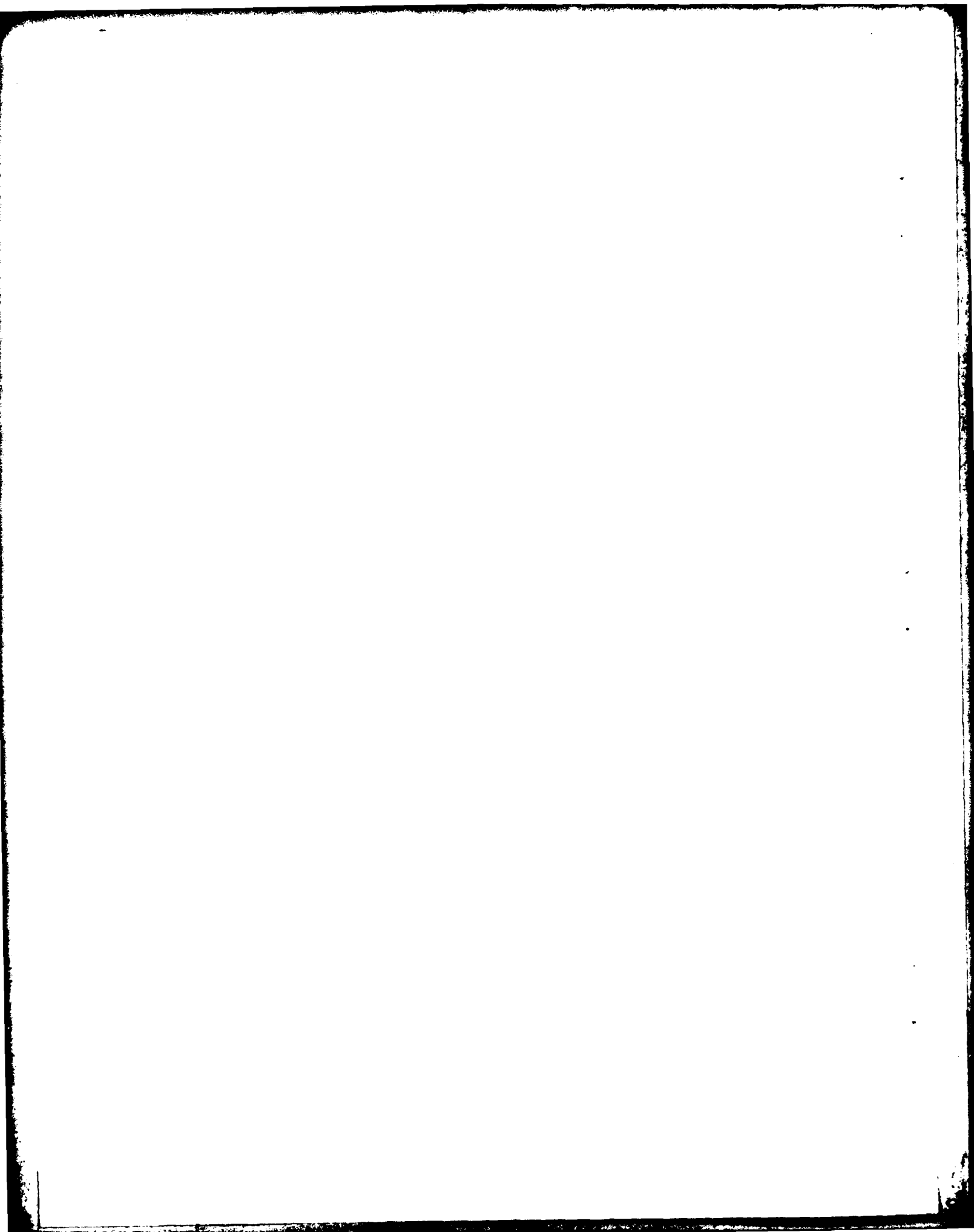
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## PREFACE

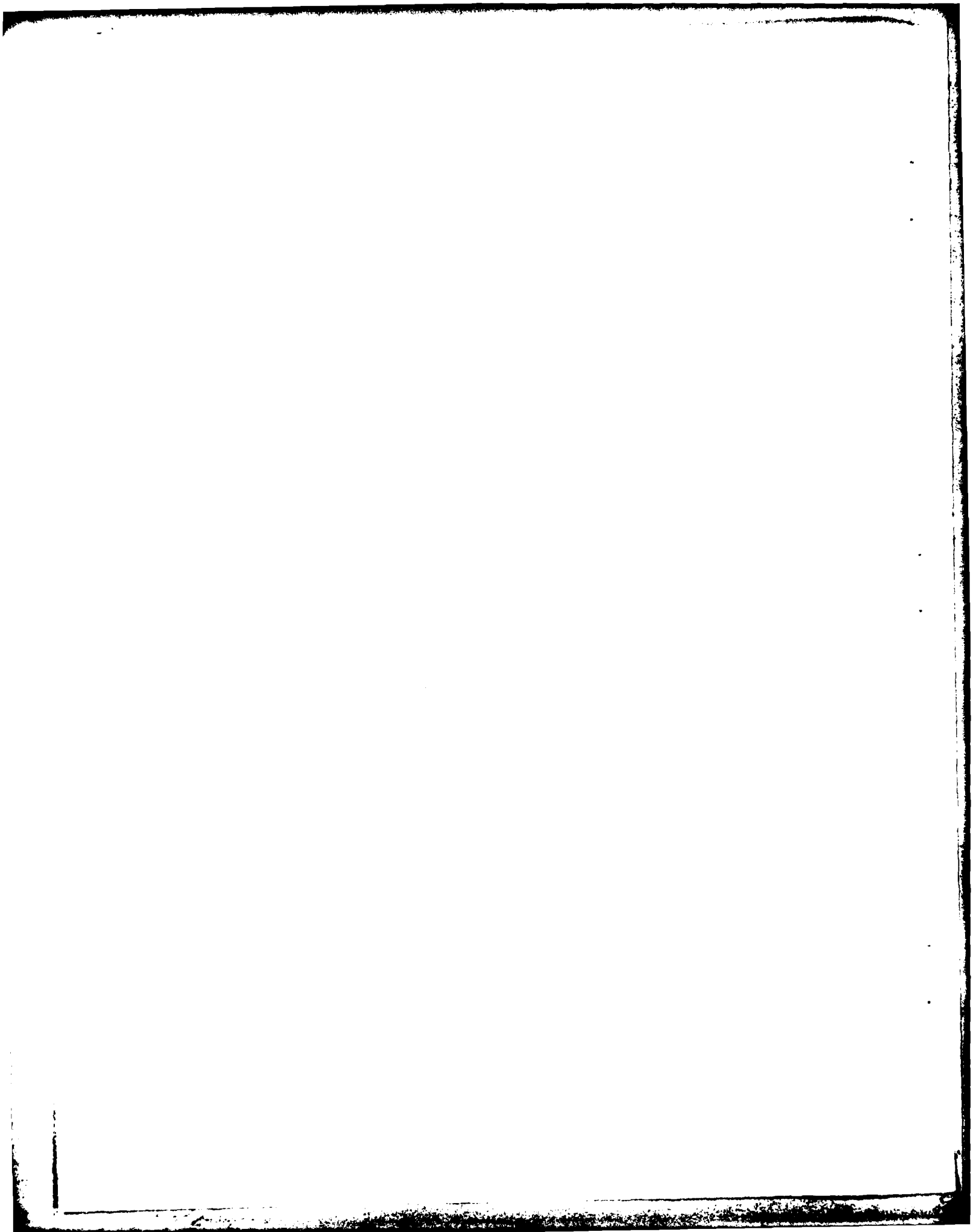
This report is an update of SAMSO-TR-73-263 (TR-0074(9260-09)-1). A calculational error in the original version of this report was discovered by D. R. Hall. The conclusions of the report are basically not affected by the error, although intermediate results differ from those originally quoted.



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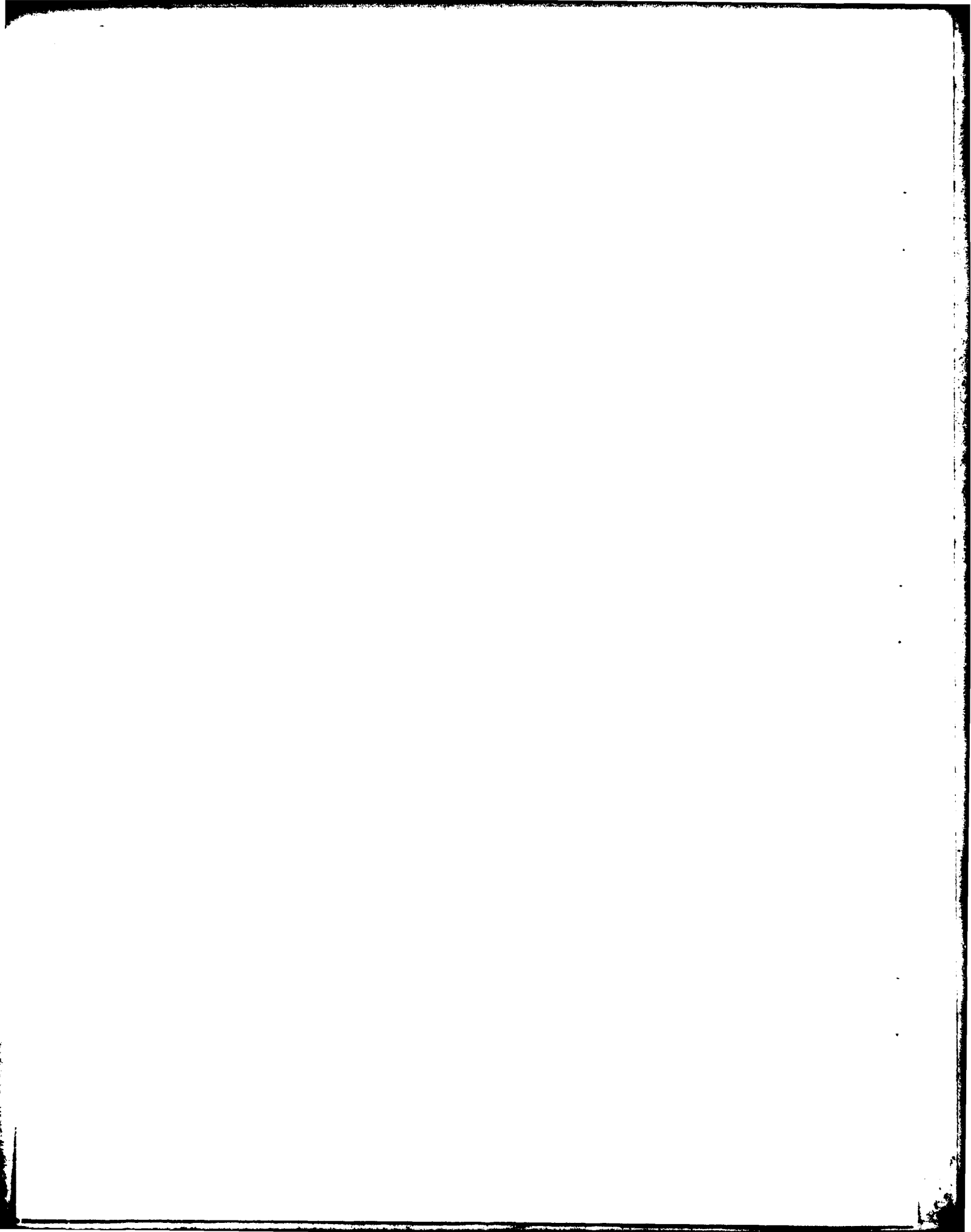
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## I. INTRODUCTION

This report describes the ionization of neutral outgas products and their attraction to a charged spacecraft. Calculations are presented as a quantitative guide to the magnitude of this effect for spacecraft at synchronous altitudes.

The problem has been reduced to a chain of separate processes. The critical questions that need to be examined are:

1. What are the efflux rates of the neutral outgas and thruster products that contribute large molecules to the spacecraft environment?
2. What fraction of these neutral molecules becomes ionized by the energetic ambient particles or the ultraviolet solar radiation encountered in space?
3. Under what conditions will the ionized molecules be returned by electrostatic forces to the spacecraft?
4. How long will it take to deposit a monolayer of molecules on the spacecraft?
5. Will the molecules reside on the surface long enough to permit a buildup of layers?

Any calculation to estimate the magnitudes of these processes depends heavily upon simplifying assumptions and upon test data, which are often scarce or must be extrapolated to fit the parameters of this problem. Nevertheless, questions 2 and 3 can be answered with some confidence (see Sections II and III respectively), so we can establish a reasonably good number for the fraction of the neutral efflux that becomes ionized and redeposited on the surface. The magnitude of the neutral efflux, however, is very poorly known. Questions 5, 4, and 1 above are discussed in Section IV. Results of this study are summarized and recommendations made in Section V. Although no attempt is made to discuss the effects of the contaminants once they are deposited, it should be noted that the effects (on, for instance,

transmissivity of optical surfaces) may be immediate (if the deposits are opaque), or delayed (if the deposits darken through some process such as polymerization), or altogether negligible.

In a previous study (Ref. 1), a calculation was made of the attraction of neutral molecules to a charged spacecraft through their polarization in the nonuniform electrostatic field of the vehicle. The resulting contamination was concluded to be negligible.

## II. FRACTIONAL IONIZATION

In order to calculate the fraction of neutral molecules that become ionized, we first consider the attenuation of a monoenergetic flux of neutral molecules due to an ionization rate  $\nu$ . Then, we shall calculate values of  $\nu$  for dominant ionization mechanisms.

The number  $g(r)$  (molecules/sec) of neutral molecules with radial velocity  $v$  passing through a spherical boundary of radius  $r$  would be constant in the absence of attenuation. If  $F_0$  (molecules/m<sup>2</sup>/sec) is the source flux of molecules from a sphere of radius  $r_0$  and a fraction  $\alpha$  of the surface is emitting, then we know the value

$$g(r_0) = 4\pi r_0^2 \alpha F_0$$

However, with an attenuation of  $\nu$  (ionizations/sec/molecule) in incremental time  $dt$ , the number of molecules/sec passing through the shell of radius  $r$  changes by

$$dg(r) = \nu g(r) dt = - \frac{\nu g(r) dr}{v} \quad (1)$$

Equation (1) is easily integrated to yield

$$g(r) = g(r_0) \exp \left[ - \frac{\nu}{v} (r - r_0) \right]$$

neutral molecules/sec passing through a shell of radius  $r$ . The number of ionizations/sec occurring inside the radius  $r$  is thus

$$g_i(r) = g(r_0) - g(r) = g(r_0) \left( 1 - \exp \left[ - \frac{\nu}{v} (r - r_0) \right] \right) \quad (2)$$

and is the same as the number of positive ions produced if each ionization removes one electron from one molecule. We can name the quantity  $\nu/\nu \equiv L$  the attenuation length where  $L$  is a measure of the radial distance required for the reduction of  $g$  by a factor of  $1/e$ .

The factor  $\nu$  needed to calculate  $L$  may be the result of either energetic particle fluxes or uv radiation. For photon fluxes,

$$\nu_{ph} = \int_0^{\infty} \sigma(E) I(E) dE \quad (3)$$

where  $\sigma(E) m^2$  is the cross section for ionization by photons of energy  $E$ , and  $I(E)$  photons/ $m^2$ /sec/eV is the intensity of the solar spectrum at energy  $E$ .

Although the solar spectrum is known (see Fig. 1 [Ref. 2]), cross sections for molecules of interest are not known at uv wavelengths. However, Feuerbacher and Fitton (Ref. 3) have calculated the photoelectron yield  $Y$  of several materials exposed to the solar spectrum. The following results from Feuerbacher and Fitton are important:

1. Typical electron yields are  $Y = 3 \times 10^{14}$  electrons/ $m^2$ /sec for aluminum. Results varied by only about a factor of 2 for other materials tested.
2. About 30 percent of the photoemission is due to Lyman  $\alpha$  (10.19 eV) photons.
3. Photoemission effectively takes place from within the first three or four atomic layers of a surface.

We shall make the assumption that the photoemission process for a surface (involving the absorption of a photon and the emission of an electron) is the same process involved in the ionization of a single, large, free molecule. This is not strictly true since, in a solid, the sharp electron energy levels of isolated atoms are broadened (Ref. 4). Weissler (Ref. 4)

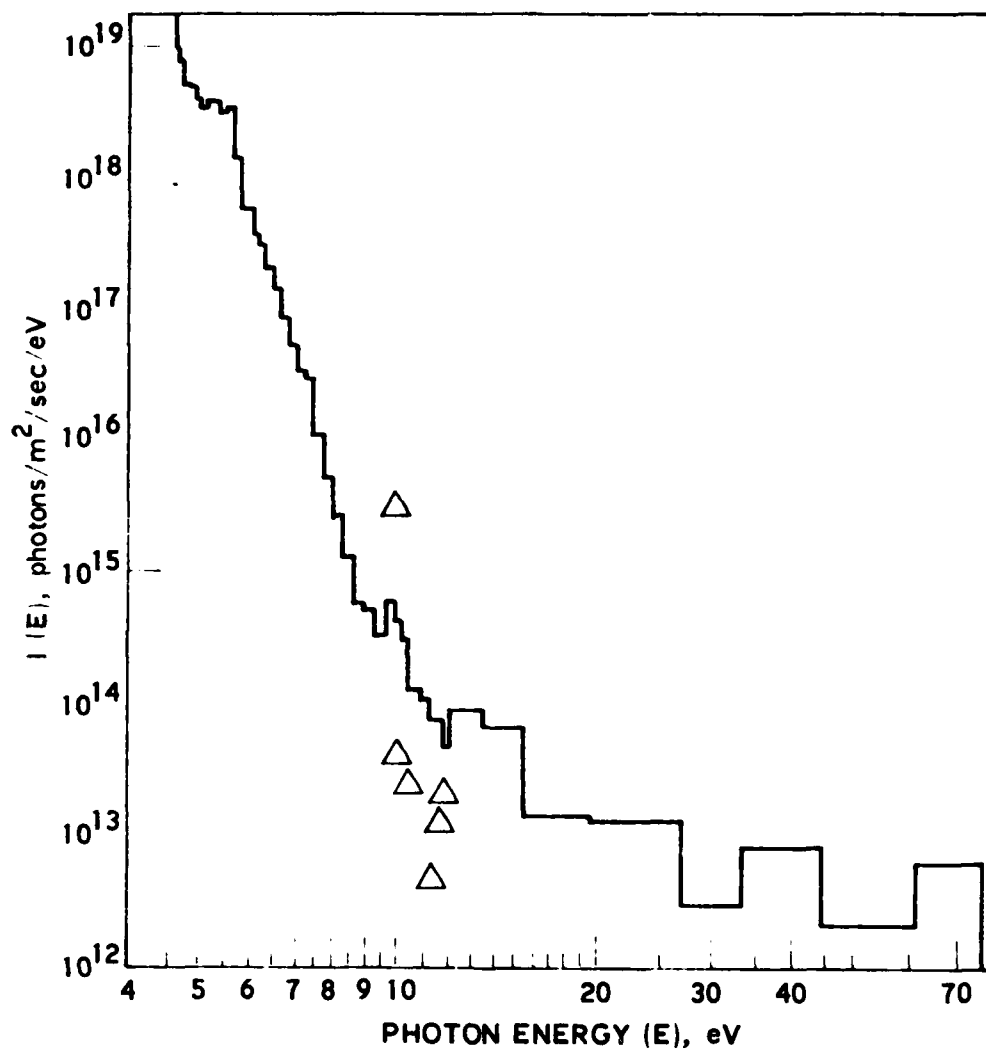


Fig. 1. The uv solar radiation flux as a function of photon energy, based on rocket and satellite observations. Discrete line emission intensities are determined by multiplying the flux (indicated by the triangles) by 1 eV (Ref. 2).



gives the photoelectric work functions of a typical solid such as aluminum as 4 eV compared with an ionization energy of 6 eV (Ref. 5).

It may be observed from Fig. 2 (Ref. 6) that the photoelectric yield between 4 and 6 eV is a small fraction of the total (note the area under the curve). Moreover, photoemission from Lyman  $\alpha$  radiation should be independent of the solid or gaseous state of the molecule because Lyman  $\alpha$  photons, with 10.19 eV, carry more energy than is required by either the work function of the solid or the ionization energy of the gas. (There is a difference, irrelevant for our purpose, in the energy of the emitted photoelectron.) The yield constancy may be understood in general terms to result from a more or less constant "packing density" of atoms in a solid where the number of electrons available for ejection is proportional to the number of atoms. We shall assume that  $Y'$ , the yield of photoelectrons per layer, is nearly constant for different substances. We can, therefore, estimate the photoelectron yield for an isolated molecule from the measurements made with solids. The quantity which Feuerbacher and Fitton (Ref. 2) measured corresponds to

$$Y = 4Y' = 4\ell n_t \int_0^{\infty} \sigma(E) I(E) dE \quad (4)$$

where  $n_t$  is the number of target particles/ $m^3$ , 4 is the number of atomic layers in the interaction region, and  $\ell$  is the atomic layer thickness. Overlap of target atoms should be negligible. The quantity  $4\ell n_t \sigma(E)$  is the probability of photoelectron emission per incident photon per eV for the surface. At this point, we specialize the calculation to a large free molecule and employ the assumption that  $Y'$ , the number of photoelectrons emitted per  $m^2/sec/layer$ , is a constant independent of the substance. A comparison of Eqs. (3) and (4) shows that

$$\nu_{ph} = \frac{2Y'}{\ell n_t} = \frac{2Y}{4\ell} \left( \frac{10^{-3} W}{\rho_o s N_A} \right) \quad (5)$$

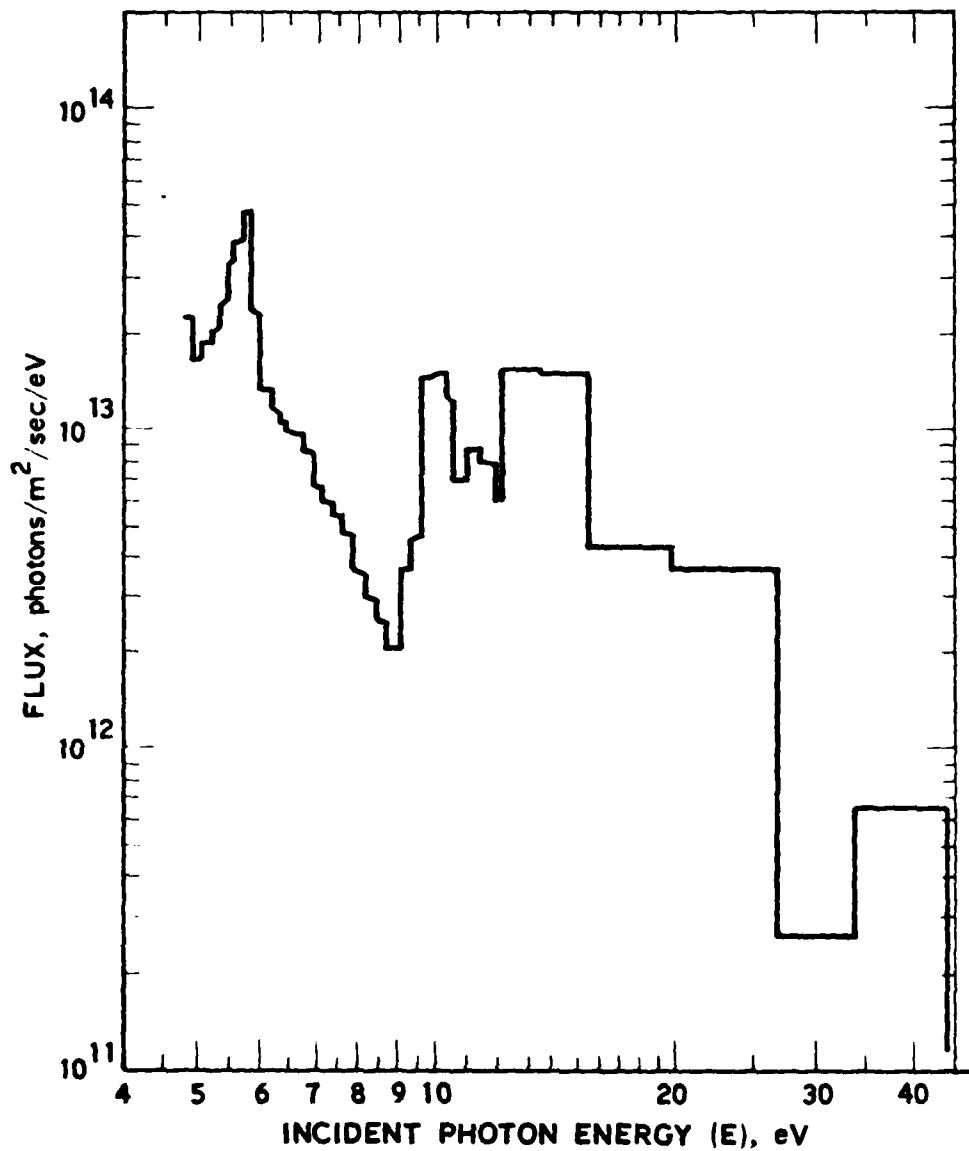


Fig. 2. Photoelectron yield of aluminum for solar irradiation excluding line emission (Ref. 6).

where the factor of 2 has been added to correct partially for the fact that any released electron escapes from an isolated molecule whereas, in the surface for which Y was measured, only photoelectrons with an outward velocity component could escape. The factor  $n_t^{-1}$  is the volume per molecule so that  $n_t^{-1} l^{-1}$  has units of area/molecule. The kg weight per mole of the target substance is  $10^{-3} W$  where W is the molecular weight. For a typical silicone of chain length 6,  $W = 458$ .  $N_A$  is Avogadro's number and is  $6.02 \times 10^{23}$  molecules/mole, S is the specific gravity of the target material and is 1.034 for silicone,  $\rho_o$  is the density of water and is  $10^3 \text{ kg/m}^3$ , and  $l$  may be evaluated from

$$l = \left( \frac{W m_n}{S \rho_o} \right)^{\frac{1}{3}}$$

where  $m_n$  is the nucleon mass  $= 1.67 \times 10^{-27} \text{ kg}$ . Evaluating Eq. (5) for heavy molecules such as silicone gives  $\nu_{ph} = 1.2 \times 10^{-4} \text{ ionizations/sec/molecule}$ .

From the numbers found, we may estimate a cross section for photoionization. We make use of Eq. (3) and the fact that 30 percent of photoemission comes from Lyman  $\alpha$  photons. Then,

$$\nu_{ph} \approx \frac{10}{3} \sigma(L\alpha) I(L\alpha)$$

where the intensity of Lyman  $\alpha$  radiation above the atmosphere is  $3 \times 10^{15} \text{ photons/m}^2/\text{sec}$  (Ref. 2). Thus, we find

$$\sigma(L\alpha) \approx 1.2 \times 10^{-20} \text{ m}^2$$

which is close to measured photoionization cross sections at higher photon energies. For example, Rich (Ref. 7) gives

$$\sigma(1425\text{\AA}) = 3.8 \times 10^{-21} \text{ m}^2$$

for silicon.

Ionization could also occur as a product of bombardment by ambient electrons or ions. For electrons, we have

$$\nu_e = \int_0^{4\pi} \int_0^\infty \sigma_e(E) \frac{dj}{dE} dE d\Omega \quad (6)$$

which gives the ionization rate  $\nu_e$  of ionizations/sec/molecule due to bombardment of a material with a cross section of  $\sigma_e(E) \text{ m}^2$  by electrons with an energy spectrum of  $dj/dE$  electrons/ $\text{m}^2/\text{sec}/\text{ster}/\text{eV}$ . We assume that:

1. The electrons are in thermal equilibrium. Thus,

$$\frac{dj}{dE} = \frac{2nE \exp - \frac{E}{e\phi_e}}{\frac{1}{2} m_e^2 (2\pi e\phi_e)^{\frac{3}{2}}}$$

where  $n$  is the ambient electron density  $\approx 10^6/\text{m}^3$  at 6 earth radii (Ref. 8),  $e$  is the electron charge  $\approx 1.6 \times 10^{-19} \text{ C}$ ,  $m_e$  is the electron mass  $\approx 9.11 \times 10^{-31} \text{ kg}$ , and  $e\phi_e$  is the most probable electron energy  $\approx 4000 \text{ eV}$  (derived from the data of DeForest and McIlwain [ Ref. 8 ]).

2. The factor  $\sigma_e(E)$  is a constant ( $\sigma_e$ ) independent of energy.
3. The electrons are isotropic.

With these assumptions, the integral in Eq. (6) can be performed, giving

$$\nu_e = n \left( \frac{8e \phi_e}{\pi m_e} \right)^{\frac{1}{2}} \sigma_e \quad (7)$$

The typical cross section for  $30 \leq E_e \leq 1000$  eV of molecules of molecular weight  $W \cong 28$  is given in Ref. 9 as  $\sigma_{32} \geq 8.8 \times 10^{-21} \text{ m}^2$ . For a molecule of silicone ( $W = 458$ ), we would expect

$$\sigma_{458} \sim \left( \frac{458}{32} \right)^{\frac{2}{3}} \sigma_{32} = 5.2 \times 10^{-20} \text{ m}^2$$

which is still  $\sim 1$  percent of the "physical" cross section of the molecule. With  $\sigma_e = \sigma_{458}$ , Eq. (7) gives

$$\nu_e = 2.2 \times 10^{-6} \text{ ionizations/sec/molecule}$$

For incident ions,  $\phi_i \approx \phi_e$ ,  $n_i \approx n$ , and  $M_i \approx 10^{+3} m_e$ , so it can be seen from Eq. (7) that  $\nu_i$  resulting from energetic ions will be considerably smaller than  $\nu_e$ .

We now return to the attenuation length

$$L = \frac{v}{\nu} = \frac{v}{\nu_{ph} + \nu_e + \nu_i}$$

where, to relate to a physical situation (particles not monoenergetic),  $v$  may be taken to be the most probable neutral molecule velocity. For  $kT = 116\text{K} = 0.01 \text{ eV} = m v^2/2$  and  $m = 458 m_n$  (silicone), we have  $v = 65 \text{ m/sec}$ .

This gives a value of

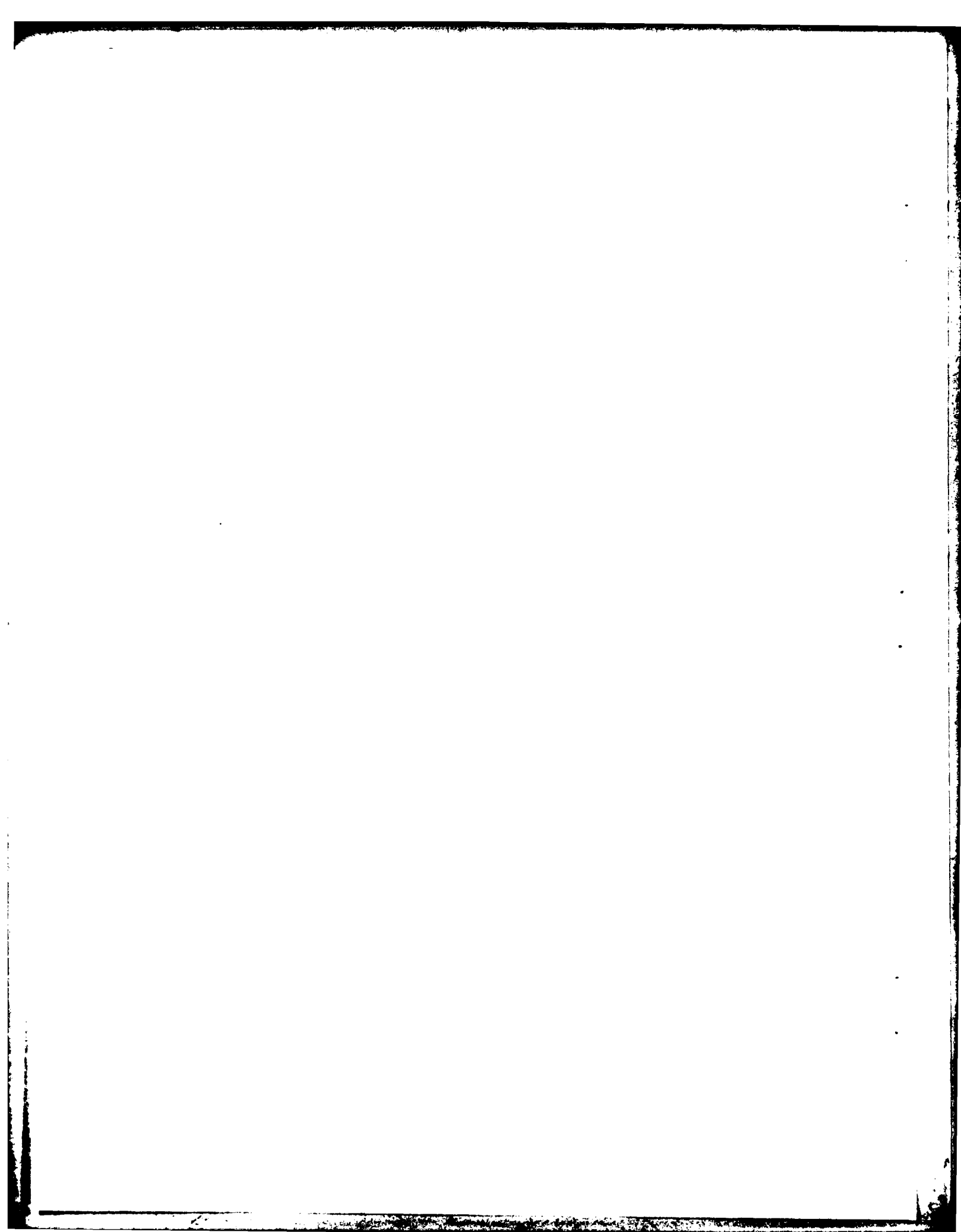
$$L = 5.4 \times 10^5 \text{ m}$$

If a neutral molecule is not ionized before it passes beyond the plasma shielding distance  $\lambda$  (about 100 m at synchronous altitude [Ref. 10]), the electrostatic force on the ion to reattract it to the charged spacecraft is considerably reduced. Consequently, we are interested primarily in the number of ions produced within  $r = \lambda = 100$  m of the spacecraft. This is given by Eq. (2) which, with  $r/L = 1.8 \times 10^{-4}$ , yields

$$\gamma \equiv \frac{g_i(\lambda)}{g(r_0)} = 1 - \exp\left(-\frac{r - r_0}{L}\right) \approx \frac{r}{L} = 1.8 \times 10^{-4} \quad (8)$$

with  $r \gg r_0$  and  $r/L \ll 1$ .

Thus, we see that 0.02 percent of the neutral (silicone) molecules will become ionized within the spacecraft sheath where electric fields may exist to reattract them to the surface.



### III. REATTRACTION MECHANICS

The possibility of whether or not a particle, once ionized, can return to the spacecraft surface must now be considered. The trajectory of an attracted particle is determined by conserving energy and angular momentum for the particle as it falls in a central field of force.

Prior to ionization, a particle has a total energy of  $E = E_0 \equiv mv_0^2/2$  where  $E_0$  is the most probable (thermal) energy of the emitting surface. At the time of ionization, the total energy of the particle is  $E = E_0 - U(r_s)$  where  $r_s$  is the radial distance of the point of ionization and  $U(r_s)$  is the potential energy of the central force field at that distance, normalized so that  $U(\infty) = 0$ . At subsequent times,  $E = E_0 - U(r)$ . With a small error for  $r < \lambda$ ,  $U(r)$  may be assumed to be the potential energy in the  $r^{-2}$  coulomb (free space) force field. The minus sign that signifies attraction has been written explicitly. If the magnitude of the negative surface potential is  $U_0 = U(r_0)$ , then  $U(r) = U_0 r_0 / r$ .

We shall consider the case of a particle emitted with maximum angular momentum  $l_0 = mv_0 r_0$  (see Fig. 3). At all subsequent times,  $l_0$  will remain the same. We shall determine whether the requirement of conservation of angular momentum ever prevents a particle from striking the surface.

The motion of a particle in the central potential  $U(r)$  is equivalent mathematically to the problem of the one-dimensional motion of a particle in a potential

$$U'(r) = \frac{l_0^2}{2m r^2} - \frac{U_0 r_0}{r}$$

(Ref. 11). Such a potential is illustrated in Fig. 4. This equivalence is evident from the energy conservation equation



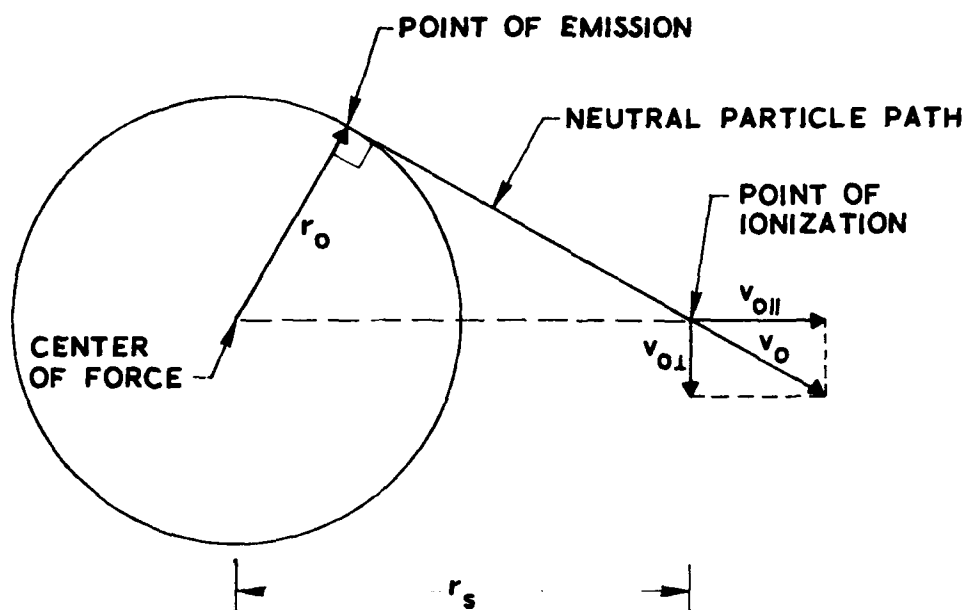


Fig. 3. Trajectory of a particle with maximum angular momentum up to point of ionization.

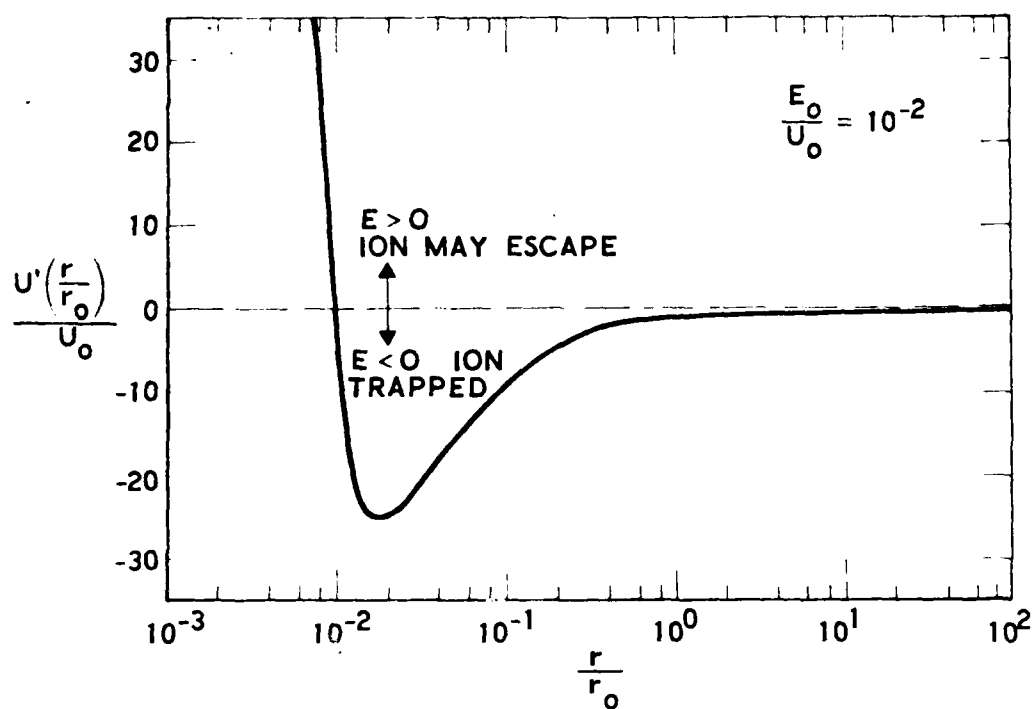


Fig. 4. Equivalent one-dimensional potential well for a particle with  $E_0/U_0 = 10^{-2}$  in an attractive  $r^{-2}$  central force field. Turning points are at values of  $r$  such that  $E = U'(r)$ .

$$E = E_o - \frac{U_o r_o}{r_s} = m\dot{r}^2 + \frac{l_o^2}{2mr^2} - \frac{U_o r_o}{r}$$

The centrifugal force term for the maximum- $l$  geometry shown in Fig. 3 can be shown to satisfy

$$\frac{l_o^2}{2mr^2} = \frac{E_o r_o^2}{r^2}$$

Turning points (apogee and perigee) of the motion are at  $r_>$ ,  $r_<$  where  $\dot{r} = 0$ . Rewriting the energy conservation equation, setting  $\dot{r} = 0$ , to examine the condition for a particle to escape (only one turning point exists) or to miss the surface (perigee at  $r_< > r_o$ ) gives

$$\frac{E_o}{U_o} - \frac{r_o}{r_s} = \frac{E_o}{U_o} \frac{r_o^2}{r^2} - \frac{r_o}{r} \quad (9)$$

Substituting  $C = E_o/U_o$ ,  $x = r/r_o$ , and  $S = r_s/r_o$ , we may write the solutions to Eq. (9) as

$$x_{\geq} = \frac{S \pm \sqrt{S^2 - 4CS(1 - CS)}}{2(1 - CS)} \quad (10)$$

From Eq. (10) it is evident that for two real solutions (bounded motion, i.e., no escape) we require

$$\frac{1}{C} > S > \frac{4C}{1 + 4C^2}$$

These conditions are plotted in Fig. 5. Note that the two lines divide the figure into three regions. If the point S where ionization occurs is too far out, the ion will escape since it is headed outward and there is no apogee turning point. The zone forbidden to ions due to angular momentum conservation, even in this worst case, does not extend above  $S = 1$ , so all particles which do not escape will hit the surface before or at perigee. If we want particles ionized as far away as 1 shielding length (e.g.,  $\lambda = 100$  m,  $r_0 = 1$  m) to be trapped, then we require  $C < 10^{-2}$ , which, if  $E_0 = 10^{-2}$  eV, will occur for surface potentials more than 1 V negative. Potentials much more negative than 1 V will occur commonly on the dark sides of spacecraft beyond the plasma-pause as well as in eclipse (Refs. 8, 12, and 13). Thus, all particles ionized within 1 shielding length from the spacecraft will return and hit the surface.

The part of the analysis dealt with in this section does not depend on the size or mass of the ion. (However, the fraction  $\gamma$  calculated in Section II is proportional to  $W^{2/3}$ .) We have assumed spherical symmetry while, in reality, only the dark side of a spacecraft will have large potentials because of the photoelectron emission on the sunlit side. Research in progress indicates that the negative potential well may extend to the sunlit side except close to the surface. However, further investigation of asymmetric spacecraft sheaths is needed.

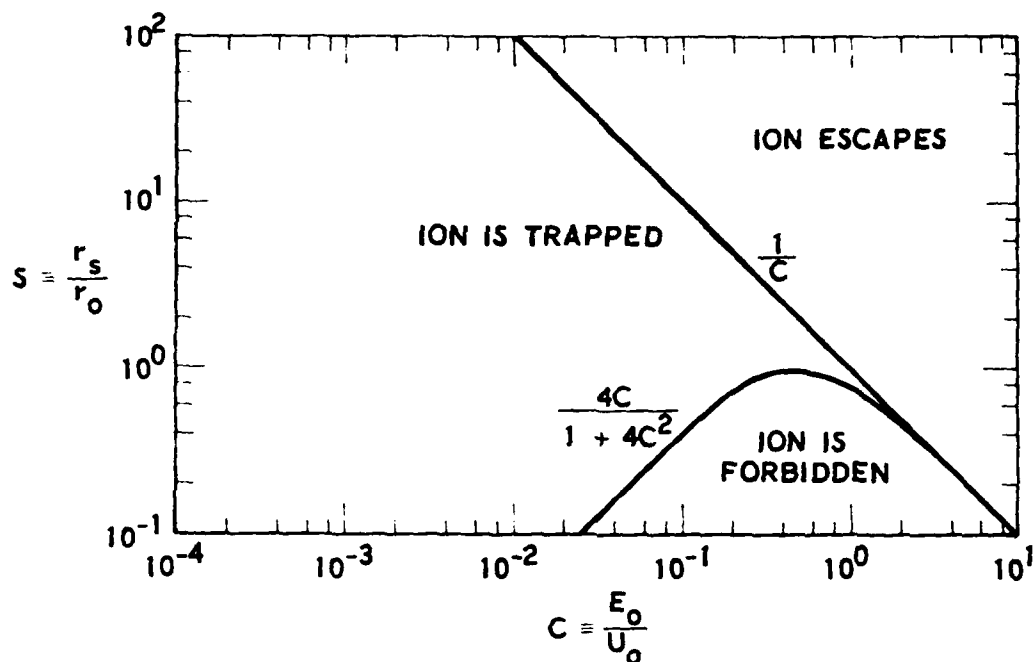


Fig. 5. Distance of ionization  $r_s/r_0$  plotted versus initial energy  $E_0/U_0$  showing regions of escape, trapping, and prohibition. The factor  $r_s$  is the radius at which ionization occurs. The radius  $r_0$  and potential  $U_0/e$  characterize the emitting surface, and  $E_0$  is the neutral particle energy.

#### IV. CONTAMINANT YIELDS

Two sources of neutral molecules will be considered: (1) outgassing effluents and (2) low level thruster impurities. Data for these quantities are not well known experimentally and are not readily available.

Outgassing is a very temperature-dependent phenomenon and, for a spinning spacecraft, temperature cycling would make net outgassing rates difficult to calculate even if laboratory data were available. Based on QCM (quartz-crystal monitor) data from the OGO-6 spacecraft, the outgassing flux may be taken to be

$$F_{og} = 3.0 \times 10^{-6} \exp\left(\frac{-t}{41.6}\right)$$

$\text{g/m}^2/\text{sec}$  with  $t$  in days.\* This number is uncertain by at least an order of magnitude.

Assuming an average propellant consumption of 0.1 lb/day and 0.5 percent impurities by weight, a total of  $2.64 \times 10^{-7}$  g/sec of impurities would be exhausted for all thrusters (Ref. 14). In relation to the area of the spacecraft surface (taken to be  $4\pi r_o^2$  with  $r_o = 1$  m), the thrusters supply an average  $F_{ti} = 2.1 \times 10^{-8}$  g/m<sup>2</sup>/sec to the spacecraft environment.

With a flux  $F(t)$  of neutral particles leaving the spacecraft and a fraction  $\gamma$  being ionized inside the shielding length, all of which return to the surface, the thickness on the surface will build up according to

$$Z(t) = \int_0^t \frac{\gamma F(t') dt'}{\rho} \quad (11)$$

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\* E. N. Borson, private communication.

where  $\rho = \rho_0 S$  is the density of the substance considered. The assumption has been made that, once deposited, the contaminant will have an infinite "sticking time." For cold surfaces such as mirror radiators, this is probably a good assumption (Ref. 14) due to the strong temperature dependence of evaporation rates. Furthermore, it is possible that the chemical form of the contaminant could be modified because of solar radiation (Ref. 15) and the modified substance might not evaporate.

Equation (11) yields

$$Z_{og} = 1.87 \times 10^{-9} \left( 1 - \exp\left(\frac{-t}{41.6}\right) \right) (\times 10^{\pm 1})$$

where  $Z_{og}$  is in meters and  $t$  is in days, so that outgassing results in a thickness of 52 Å buildup with an e-folding time of about 42 days. For thruster impurities,  $F$  is a constant, and Eq. (11) gives

$$Z_{ti} = 3.2 \times 10^{-13} t$$

where  $Z_{ti}$  is in meters and  $t$  is in days.

Parameters for silicone have been used throughout. The quantities  $Z_{og}$  and  $Z_{ti}$  are plotted as Curves 2 and 5 respectively in Fig. 6. The results are discussed in Section V.

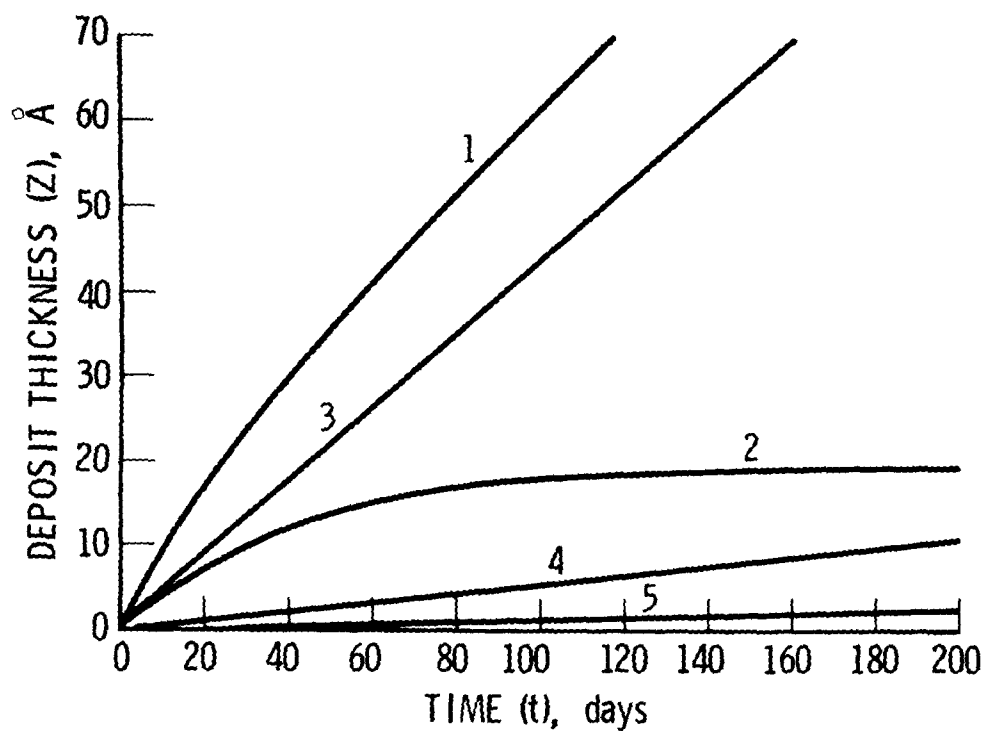
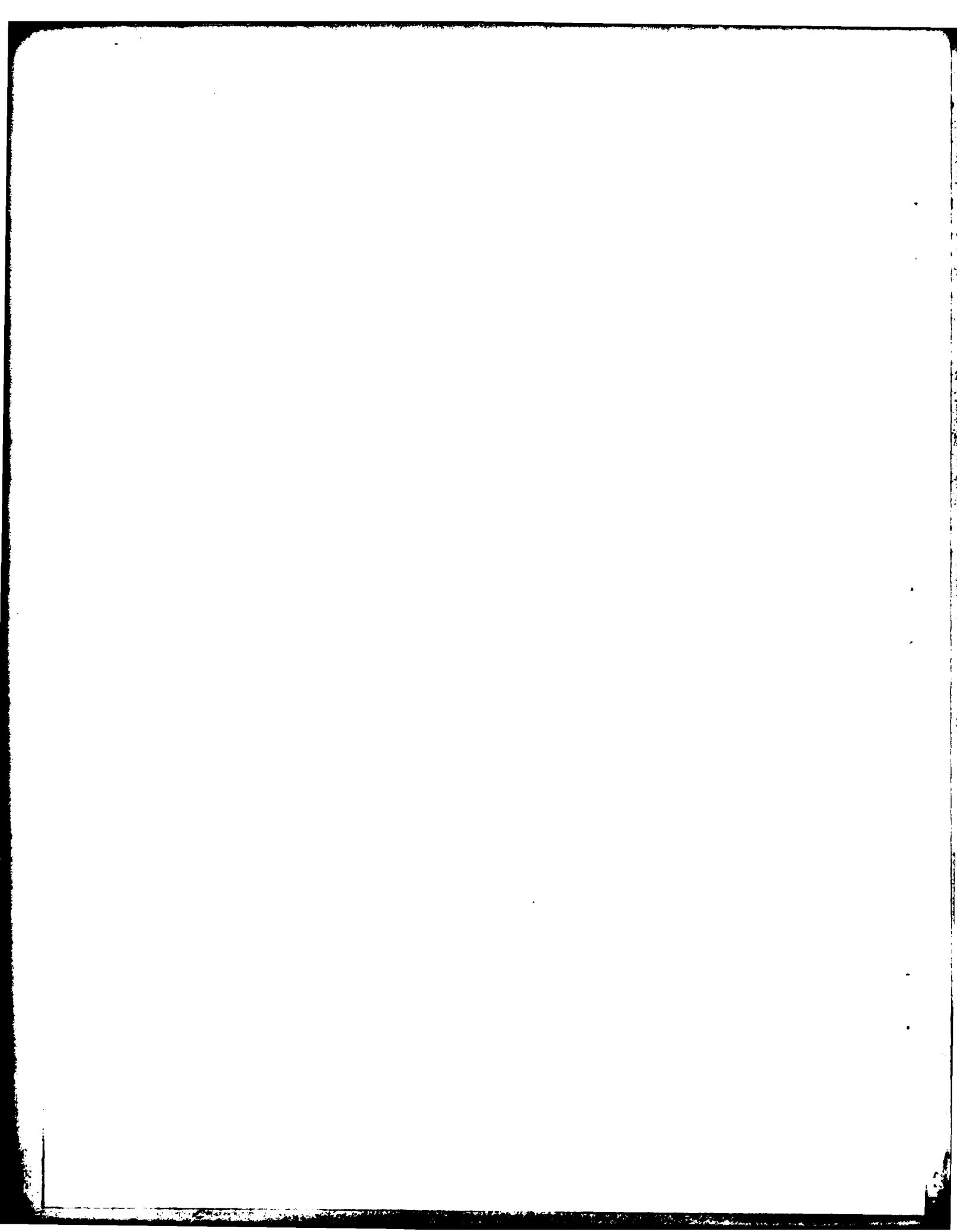


Fig. 6. Deposit thickness as a function of time showing:

- 1 - Total of 2 and 3.
- 2 - Reattracted ionized outgas products.
- 3 - Direct impingement of impurities from low level thrusters on Type I radiators.
- 4 - Direct impingement of impurities from low level thrusters on Type II radiators.
- 5 - Reattracted ionized impurities from low level thrusters.





## V. SUMMARY AND CONCLUSIONS

It was shown in Section II that  $\gamma = 0.02$  percent of the heavy neutral spacecraft effluents would be ionized within the spacecraft sheath. At altitudes of 6.6 earth radii, ambient energetic electrons and solar uv radiation contribute comparably to the ionization rate. The quantity  $\gamma$  is probably accurate to closer than a factor of 5.

In Section III it was demonstrated that all of these ions would be reattracted to the spacecraft surface when it is negatively charged. Outgassing and thruster effluent rates were discussed in Section IV. Outgassing rates are uncertain by at least an order of magnitude.

The contaminant thicknesses calculated in Section IV are shown in Fig. 6. Negligible re-evaporation has been assumed. Curve 2 is the contamination buildup resulting from the reattraction of ionized outgas products. Curve 5, which by comparison is negligible, results from the reattraction of ionized thruster effluents. Included in Fig. 6 are the thicknesses of deposits due to direct impingement of thruster impurities (assumed to be 0.5 percent of the propellant by weight) on Type I (Curve 4) and Type II (Curve 5) radiators, as calculated by Borson (Ref. 14). A numerical error found in Ref. 14 has been corrected in plotting these curves. Inasmuch as perhaps  $100 \text{ \AA}$  of deposit is required for significant optical and thermal degradation of a sensitive surface, it is clear that only two of these effects have significance within the first 6 months of the satellite lifetime, i. e., direct thruster impingement on Type I radiators and outgas reattraction. The combined deposit due to these two effects is shown as Curve 1 in Fig. 6. A total thickness of  $100 \text{ \AA}$  is predicted to result in about 6 months.

It is concluded that ionization and subsequent reattraction of spacecraft outgas products may play a significant role in depositing large molecules on a satellite surface during the early months in orbit. Subsequently, this effect contributes negligible additional deposits. However, spacecraft thermal effects attributed to optical surface contamination have time scales of 6 months and longer.\* This evidence can be interpreted in several ways:

1. Some other mechanism more nearly linear in time (e.g., direct thruster impurity impingement, shown as Curve 3) becomes dominant.
2. Deposits darken or change chemically in time due to another mechanism, e.g., by polymerization (Refs. 15, 16, and 17). Thus, as long as a sufficient thickness of contaminant has been deposited shortly after launch and evaporation of it is negligible, continual deposition is not necessary.
3. Outgassing is not monotonically time-dependent (e.g., is it stimulated by magnetic storms?).
4. The magnitude and time scales of outgassing are in reality much larger than estimated (an order of magnitude would do).
5. Some other mechanism is responsible.

Due to the uncertainty in  $F_{og}$ , the predicted importance of outgas product reattraction is not certain. However, estimates of other mechanisms suffer from similar uncertainties. Combinations of explanations 1, 2, 3, and 4 above are not ruled out.

To verify these predictions, the following information is required:

1. The average outgas rates and composition.
2. Thruster impurity fractions and composition.
3. Ionization cross sections for uv and electron bombardment for various contaminant substances.
4. Spacecraft potentials and their spin dependence.
5. Spacecraft sheath electric field magnitudes and geometries.

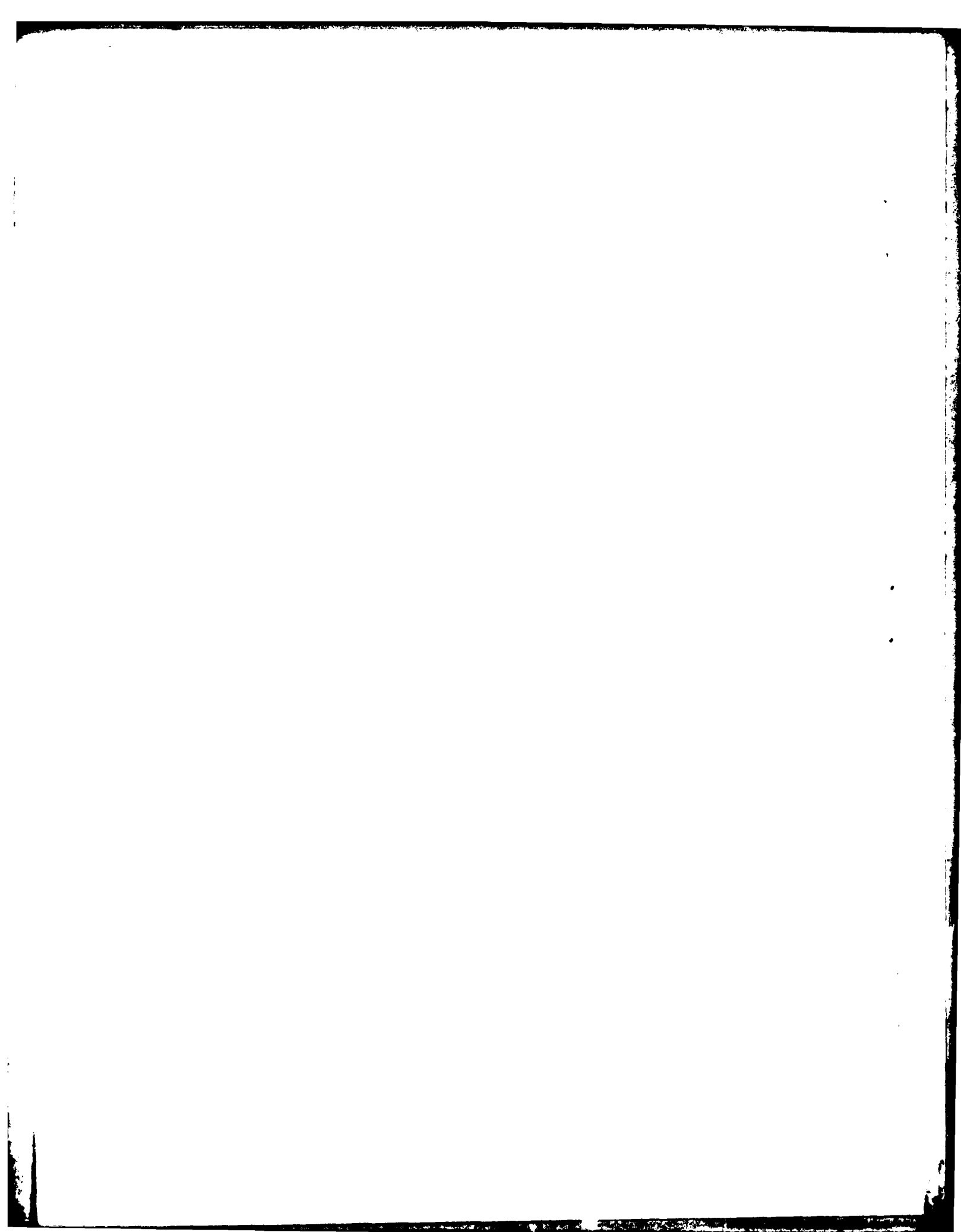
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\* D. W. Moore, personal communication.

6. Ion orbits in asymmetric sheaths.
7. Contaminant sticking times.

To combat the contamination caused by ionization of outgas materials, several methods are possible (see also Ref. 18):

1. Decoy the ions by electrostatic means as detailed by Cauffman (Ref. 19).
2. Reduce outgas fluxes through redesign, material substitution, or prelaunch bakeout.
3. Reduce the spacecraft attractive electric fields by coating insulating surfaces with thin, transparent, conductive films.



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